US010077644B2

(12) **United States Patent**
Storslett et al.

(10) **Patent No.: US 10,077,644 B2**
(45) **Date of Patent: *Sep. 18, 2018**

(54) **METHOD AND APPARATUS FOR GENERATING HIGH-PRESSURE PULSES IN A SUBTERRANEAN DIELECTRIC MEDIUM**

(71) Applicant: **Chevron U.S.A. Inc.**, San Ramon, CA (US)

(72) Inventors: **Stein J. Storslett**, Bakersfield, CA (US); **Rick B. Spielman**, Pocatello, ID (US)

(73) Assignee: **CHEVRON U.S.A. INC.**, San Ramon, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 317 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **14/208,525**

(22) Filed: **Mar. 13, 2014**

(65) **Prior Publication Data**

US 2014/0262226 A1 Sep. 18, 2014

Related U.S. Application Data

(60) Provisional application No. 61/868,391, filed on Aug. 21, 2013, provisional application No. 61/801,304, filed on Mar. 15, 2013.

(51) **Int. Cl.**
E21B 43/26 (2006.01)
E21B 28/00 (2006.01)

(52) **U.S. Cl.**
CPC ***E21B 43/26*** (2013.01); ***E21B 28/00*** (2013.01)

(58) **Field of Classification Search**
CPC E21B 43/26
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

672,231	A	4/1901	Lacomme
696,647	A	4/1902	Lacomme
781,619	A	1/1905	Rogers
1,152,697	A	9/1915	Bodde
1,253,570	A	1/1918	Berry
1,315,540	A	9/1919	Curme, Jr.

(Continued)

FOREIGN PATENT DOCUMENTS

WO	2003/069110	A1	8/2003
WO	2006/023998	A2	3/2006
WO	2010/027866	A2	3/2010

OTHER PUBLICATIONS

Cho, S.H., et al; "Dynamic Fragmentation of Rock by High-Voltage Pulses"; ARMA/USRMS 06-1118, 41st U.S. Symposium on Rock Mechanics (USRMS), Jun. 2006, 9 pages.

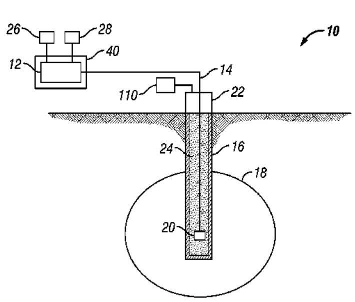
(Continued)

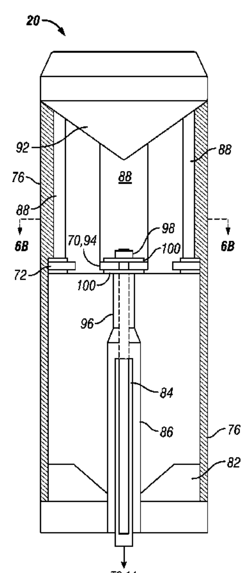
Primary Examiner — D. Andrews

(57) **ABSTRACT**

An apparatus and method for generating high-pressure pulses in a subterranean dielectric medium are provided. The method includes providing an electrode assembly in the medium, the electrode assembly having first and second electrodes that define a gap therebetween. A shaped electric current pulse is delivered to the electrode assembly. The electric current pulse has a duration greater than 100 μs so that an electric arc is formed between the first and second electrodes, thereby producing a pressure pulse in the medium.

22 Claims, 4 Drawing Sheets





(56) **References Cited**

U.S. PATENT DOCUMENTS

1,376,180 A 4/1921 Wickersham
1,744,173 A 1/1930 Longhi
1,861,332 A 5/1932 Waitz
2,162,823 A 6/1939 Phillippi et al.
2,167,536 A 7/1939 Suits
2,403,990 A 7/1946 Mason
2,559,227 A 7/1951 Rieber
2,617,080 A 11/1952 Nims
2,660,556 A 11/1953 Butler
2,822,148 A 2/1958 Murray
2,870,376 A 1/1959 Tognola
2,871,943 A 2/1959 Bodine, Jr.
2,887,604 A 5/1959 Bodine, Jr.
2,931,947 A 4/1960 Fruengel
2,946,217 A 7/1960 Fruengel
3,007,133 A 10/1961 Padberg, Jr.
3,016,095 A 1/1962 Bodine
3,129,403 A 4/1964 Harter
3,149,372 A 9/1964 Stinger
3,157,498 A 11/1964 Zernow et al.
3,158,207 A 11/1964 Rowley
3,160,952 A 12/1964 Corney et al.
3,163,141 A 12/1964 Wesley et al.
3,169,577 A 2/1965 Sarapuu
3,179,187 A 4/1965 Sarapuu
3,180,418 A 4/1965 MacLeod
3,181,328 A 5/1965 Zeitlin
3,181,799 A 5/1965 Wurzburg et al.
3,188,844 A 6/1965 Schwinghamer
3,200,626 A 8/1965 Callender
3,203,212 A 8/1965 Simicich
3,207,447 A 9/1965 Whitham
3,208,674 A 9/1965 Bailey
3,220,873 A 11/1965 Wesley
3,222,902 A 12/1965 Brejcha et al.
3,225,252 A 12/1965 Schrom et al.
3,225,578 A 12/1965 Krieger
3,228,221 A 1/1966 Zernow et al.
3,232,085 A 2/1966 Inoue
3,232,086 A 2/1966 Inoue
3,234,429 A 2/1966 Schrom
3,245,032 A 4/1966 Knott et al.
3,248,917 A 5/1966 Herring, Jr.
3,251,027 A 5/1966 Huckabay et al.
3,253,442 A 5/1966 Grove, Jr. et al.
3,267,710 A 8/1966 Inoue
3,267,780 A 8/1966 Roth
3,268,028 A 8/1966 Miller
3,273,365 A 9/1966 Felts
3,282,294 A 11/1966 Corniello
3,286,226 A 11/1966 Kearsley et al.
3,304,533 A 2/1967 Huckabay et al.
3,332,510 A 7/1967 Clark
3,338,080 A 8/1967 Golden
3,352,503 A 11/1967 Maroudas
3,354,344 A 11/1967 Schrom
3,356,178 A 12/1967 Nash, Jr.
3,358,487 A 12/1967 Brejcha et al.
3,364,708 A 1/1968 Padberg, Jr.
3,366,564 A 1/1968 Allen
3,368,194 A 2/1968 Cholet et al.
3,369,217 A 2/1968 Luehrmann et al.
3,371,404 A 3/1968 Lemelson
3,376,633 A 4/1968 Wesley
3,386,507 A 6/1968 Lumpkin
3,394,569 A 7/1968 Smith
3,401,473 A 9/1968 Schrom et al.
3,402,120 A 9/1968 Allen et al.
3,403,375 A 9/1968 Wright, Jr. et al.
3,408,432 A 10/1968 Tumm et al.
3,416,128 A 12/1968 Allen
3,418,835 A 12/1968 Erlandson
3,423,979 A 1/1969 Smith et al.
3,428,940 A 2/1969 Huckabay
3,452,565 A 7/1969 Cadwell
3,458,858 A 7/1969 Wright, Jr.
3,486,062 A 12/1969 Schrom
3,491,010 A 1/1970 Ishibashi
3,500,942 A 3/1970 Smith, Jr.
3,512,384 A 5/1970 Inoue
3,522,167 A 7/1970 Allen
3,537,542 A 11/1970 Dubois et al.
3,555,866 A 1/1971 Roth
3,566,645 A 3/1971 Lemelson
3,566,647 A 3/1971 Inoue
3,572,072 A 3/1971 Hundley et al.
3,575,631 A 4/1971 Pratt
3,583,766 A 6/1971 Padberg, Jr.
3,588,580 A 6/1971 Vining
3,593,551 A 7/1971 Roth et al.
3,594,115 A 7/1971 Wesley et al.
3,603,127 A 9/1971 Seiffert et al.
3,613,823 A 10/1971 Burrage
3,679,007 A 7/1972 O'Hare
3,688,535 A 9/1972 Keinanen et al.
3,700,169 A 10/1972 Naydan et al.
3,708,022 A 1/1973 Woodruff
3,715,082 A 2/1973 Carley-Macauly et al.
3,725,226 A 4/1973 Stoner
3,728,671 A 4/1973 Poston, Jr.
3,742,746 A 7/1973 Erlandson
3,748,034 A 7/1973 Luebbe
3,750,441 A 8/1973 Schneider et al.
3,786,662 A 1/1974 Roth
3,796,463 A 3/1974 Naydan et al.
3,797,294 A 3/1974 Roth
3,822,747 A 7/1974 Maguire, Jr.
3,840,078 A 10/1974 Allgood et al.
3,840,270 A 10/1974 Allgood, Jr.
3,842,907 A 10/1974 Baker et al.
3,874,450 A 4/1975 Kern
3,881,559 A 5/1975 Allgood et al.
3,923,099 A 12/1975 Brandon
3,931,856 A 1/1976 Barnes
3,946,809 A 3/1976 Hagedorn
3,965,982 A 6/1976 Medlin
3,990,512 A 11/1976 Kuris
4,039,042 A 8/1977 Edwards et al.
4,066,544 A 1/1978 Stark
4,074,758 A 2/1978 Scott
4,076,980 A 2/1978 Arnold et al.
4,084,637 A 4/1978 Todd
4,084,638 A 4/1978 Whiting
4,084,639 A 4/1978 Todd
4,135,579 A 1/1979 Rowland
4,164,978 A 8/1979 Scott
4,169,029 A 9/1979 Smirnov et al.
4,169,503 A 10/1979 Scott
4,196,329 A 4/1980 Debettencourt
4,313,573 A 2/1982 Goldberger et al.
4,343,356 A 8/1982 Riggs et al.
4,345,650 A 8/1982 Wesley
4,401,162 A 8/1983 Osborne
4,458,153 A 7/1984 Wesley
4,471,838 A 9/1984 Bodine
4,479,680 A 10/1984 Wesley et al.
4,487,264 A * 12/1984 Hyne E21B 43/24
166/300
4,525,612 A 6/1985 Kawashima
4,527,085 A 7/1985 Bohan, Jr. et al.
4,540,127 A 9/1985 Andres
4,550,779 A 11/1985 Zakiewicz
4,567,945 A 2/1986 Segalman
4,630,607 A 12/1986 Duinker et al.
4,640,353 A 2/1987 Schuh
4,649,997 A 3/1987 Bousaid
4,651,311 A 3/1987 Owen et al.
4,651,825 A 3/1987 Wilson
4,653,697 A 3/1987 Codina
4,667,738 A 5/1987 Codina
4,715,376 A 12/1987 Nowacki et al.
4,734,894 A 3/1988 Cannelli et al.
4,741,405 A 5/1988 Moeny et al.
4,917,785 A 4/1990 Juvan

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,957,606	A	9/1990	Juvan
4,990,732	A	2/1991	Dudko et al.
5,004,050	A	4/1991	Sizonenko et al.
5,026,484	A	6/1991	Juvan
5,049,822	A	9/1991	Zoltan
5,105,154	A	4/1992	Givens
5,106,164	A	4/1992	Kitzinger et al.
5,151,630	A	9/1992	Boy et al.
5,228,011	A	7/1993	Owen
5,282,508	A	2/1994	Ellingsen et al.
5,287,382	A	2/1994	Destannes et al.
5,301,169	A	4/1994	Baria et al.
5,368,724	A	11/1994	Ayers et al.
5,386,877	A	2/1995	Codina
5,398,217	A	3/1995	Cannelli et al.
5,425,570	A	6/1995	Wilkinson
5,430,346	A	7/1995	Johnson
5,432,756	A	7/1995	Bryden
5,464,513	A	11/1995	Goriachev et al.
5,482,357	A	1/1996	Wint et al.
5,573,307	A	11/1996	Wilkinson
5,731,655	A	3/1998	Corrado
5,773,750	A	6/1998	Jae et al.
5,896,938	A	4/1999	Moeny et al.
5,948,171	A	9/1999	Grothaus
6,018,502	A	1/2000	Fry, Jr.
6,080,029	A	6/2000	Johnson et al.
6,094,809	A	8/2000	Grassi
6,145,934	A	11/2000	Arai et al.
6,164,388	A	12/2000	Martunovich et al.
6,215,734	B1	4/2001	Moeny et al.
6,227,293	B1	5/2001	Huffman et al.
6,269,883	B1	8/2001	Gissler et al.
6,414,419	B1	7/2002	Kim
6,427,774	B2	8/2002	Thomas et al.
6,457,778	B1	10/2002	Chung et al.
6,591,649	B1	7/2003	Gafri et al.
6,705,425	B2	3/2004	West
6,761,416	B2	7/2004	Moeny et al.
6,978,672	B1	12/2005	Chen
7,037,040	B2	5/2006	Phillips
7,233,150	B2	6/2007	Chen
7,270,195	B2	9/2007	MacGregor et al.
7,384,009	B2	6/2008	Moeny
7,398,823	B2	7/2008	Montgomery
7,416,032	B2	8/2008	Moeny et al.
7,493,787	B2	2/2009	Golovashchenko et al.
7,527,108	B2	5/2009	Moeny
7,530,406	B2	5/2009	Moeny et al.
7,674,723	B2	3/2010	Porshnev et al.
7,677,673	B2	3/2010	Tranquilla et al.
7,721,428	B2	5/2010	Stoving et al.
8,172,006	B2	5/2012	Moeny
8,186,454	B2	5/2012	Moeny
8,220,537	B2	7/2012	Leon
8,227,779	B2	7/2012	Neff
8,253,417	B2	8/2012	Pislak
8,596,349	B2	12/2013	Leon et al.
8,614,580	B2	12/2013	Combee
9,394,776	B2	7/2016	Leon et al.
2003/0205376	A1	11/2003	Ayoub
2005/0150688	A1	7/2005	MacGregor
2005/0167099	A1	8/2005	Phillips
2005/0183858	A1	8/2005	Ayoub
2005/0279161	A1	12/2005	Chen
2005/0279497	A1	12/2005	Chen
2005/0280419	A1	12/2005	Chen
2006/0038437	A1	2/2006	Moeny
2006/0151166	A1	7/2006	Montgomery
2006/0208738	A1	9/2006	Moore
2007/0152494	A1	7/2007	Moeny
2007/0175502	A1	8/2007	Sliwa et al.
2008/0041462	A1	2/2008	Janway et al.
2008/0277508	A1	11/2008	Moeny
2009/0050371	A1*	2/2009	Moeny E21B 7/15 175/57
2009/0294121	A1	12/2009	Leon
2011/0011592	A1	1/2011	Leon
2011/0308789	A1	12/2011	Zhang
2012/0146650	A1	6/2012	Combee
2012/0194196	A1	8/2012	Combee
2012/0256634	A1	10/2012	Morys
2013/0255936	A1	10/2013	Geilikman et al.
2013/0312957	A1	11/2013	Grimes
2014/0008072	A1	1/2014	Rey-Bethbeder
2014/0008073	A1	1/2014	Rey-Bethbeder et al.
2014/0060814	A1	3/2014	Leon
2014/0262227	A1	9/2014	Storslett et al.

OTHER PUBLICATIONS

Cho, Sang Ho., et al.; "Influence of the Applied Pressure Waveform on the Dynamic Fracture Processes in Rock"; 2004, International Journal of Rock Mechanics & Mining Sciences, vol. 41, pp. 771-784.

Dubovenko, K.V., et al.; "Underwater Electrical Discharge Characteristics at High Values of Initial Pressure and Temperature"; Abstract, 25th IEEE International Conference on Plasma Science, 1998.

Hammon, Jud, et al.; "Electric Pulse Rock Sample Disaggregator"; IEEE International Pulsed Power Conference, 2001, 4 pages.

Loeffler, M., et al.; "Electrical Wire Explosions as a Basis for Alternative Blasting Techniques"; International Conference on Pulsed Power Applications, Mar. 2001, pp. E.16/1-E.16/7.

Madhavan, S., et al.; "Modeling of Shock-Wave Generation in Water by Electrical Discharges"; IEEE Transactions on Plasma Science, vol. 28, No. 5, Oct. 2000, pp. 1552-1557.

Nelson, Lloyd S., et al.; "Aluminum-Enhanced Underwater Electrical Discharges for Steam Explosion Triggering"; Jul. 1999, Sandia National Laboratories Report—SAND99-0796, pp. iii-45.

Sarkar, P., et al.; "Operation of a Capacitor Bank for Plasma Metal Forming"; 2000, Indian Academy of Sciences, vol. 55, Nos. 5 & 6, pp. 941-945.

Touryan, K.J., et al.; "Electrohydraulic Rock Fracturing by Pulsed Power"; 7th IEEE Conference on Pulsed Power 1, (1989), pp. 69-72.

Wakeland, P., et al.; "Hydrodynamic Loading of Structural Components Due to Electrical Discharge in Fluids"; 14th IEEE Conference on Pulsed Power 2, Jun. 2003, pp. 925-928.

Weise, Th. H.G.G., et al.; "Experimental Investigations on Rock Fracturing by Replacing Explosives with Electronically Generated Pressure Pulses"; 1993, 9th IEEE Conference on Pulsed Power 1, pp. 19-22.

Andres, U., et al.; "Liberation of Mineral Constituents by High-Voltage Pulses"; Powder Technology, 1986, vol. 48, pp. 269-277.

Andres, U.; "Liberation Study of Apatite—Nepheline Ore Comminuted by Penetrating Electrical Discharges"; International Journal of Mineral Processing, 1977, vol. 4, pp. 33-38.

Andres, U.; "Parameters of Disintegration of Rock by Electrical Pulses"; 1989, Powder Technology, vol. 58, pp. 265-269.

Hasebe, Tadashi, et al.; "Focusing of Shock Wave by Underwater Discharge on Nonlinear Reflection and Focusing Effect"; English Abstract, J. Soc. Mat. Sci., Japan, vol. 45, No. 10, Oct. 1996.

Hawrylewicz, B.M., et al.; "Experiment with Electric Discharge in Rock Splitting"; Sym. on Rock Mechanics, 1986, Chapter 62, pp. 429-435.

Mao, Ronghai, et al.; "Experiments on Pulse Power Fracturing"; SPE 153805, Mar. 2012, pp. 1-16.

Maurer, William C.; "Spark Drilling"; 1969, Soc. Mining Eng. Proc. of the 11th Sym. on Rock Mechanics, Chapter 33, pp. 687-703.

McClung, I. Buford; "The Feasibility of Developing a Borehole Sparker for Geothermal Wells"; Jan. 1977, EG&G Energy Measurements, Inc., 1997, LOA 217, Title Page, Disclaimer, Acknowledgements, Table of Contents p. v, pp. 1-17.

Pierce, K.G., et al.; "Advanced Drilling Systems Study"; 1995, Sandia National Laboratories Report, SAND95-0331, Distribution Category UC-258, Title Page, Acknowledgements, Table of Contents, pp. I-1 through III-44 (Part 1).

(56) **References Cited**

OTHER PUBLICATIONS

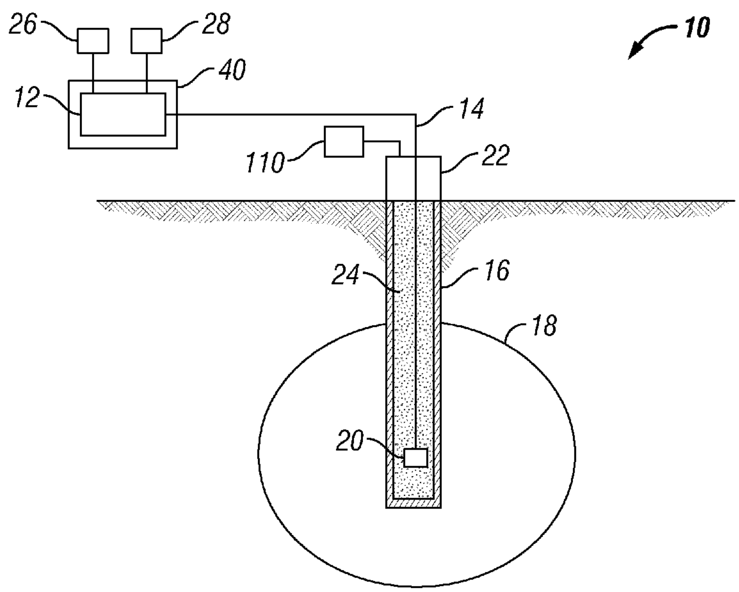
Pierce, K.G., et al.; "Advanced Drilling Systems Study"; 1995, Sandia National Laboratories Report, SAND95-0331, Distribution Category UC-258, pp. III-45 through V-39 (Part 2).

Pierce, K.G., et al.; "Advanced Drilling Systems Study"; 1995, Sandia National Laboratories Report, SAND95-0331, Distribution Category UC-258, pp. V-40 through IX-26, Distribution—5 pages (Part 3).

International Search Report, dated May 16, 2011, during the prosecution of International Application No. PCT/US2008/084662.

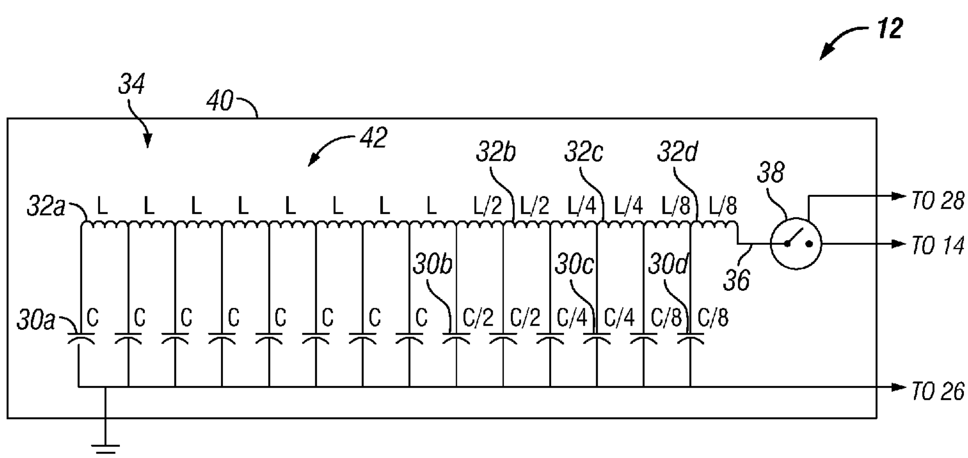
Written Opinion of the International Searching Authority, dated May 16, 2011, during the prosecution of International Application No. PCT/US2008/084662.

* cited by examiner



10
26
28
40
12
14
110
22
24
16
18
20

FIG. 1



12
34
40
42
32a
32b
32c
32d
38
L
L/2
L/4
L/8
TO 28
TO 14
36
30a
30b
30c
30d
C
C/2
C/4
C/8
TO 26

FIG. 2

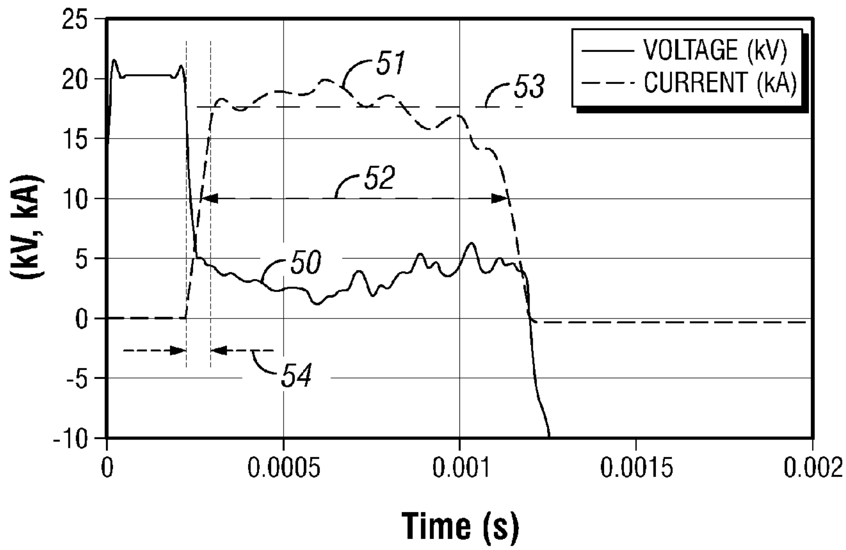

VOLTAGE (kV)
CURRENT (kA)
25
20
15
10
5
0
-5
-10
(kV, kA)
0
0.0005
0.001
0.0015
0.002
Time (s)
50
51
52
53
54

FIG. 3

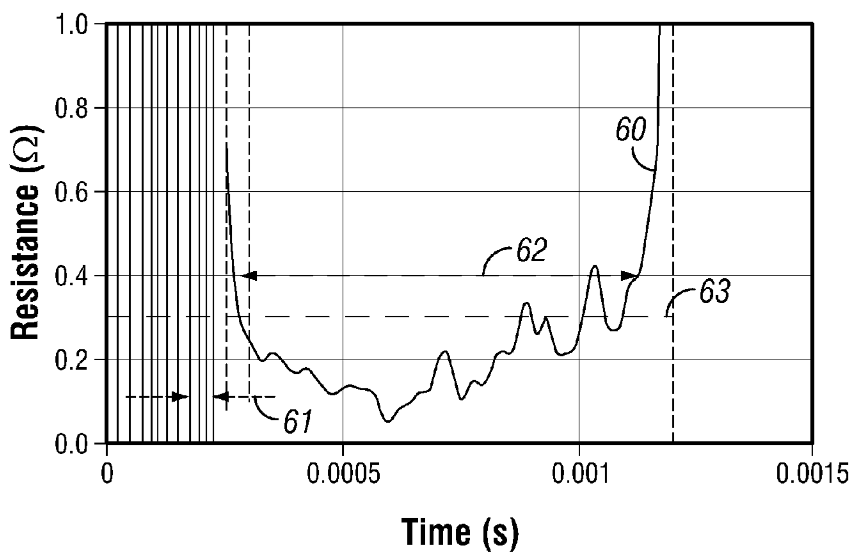

1.0
0.8
0.6
0.4
0.2
0.0
Resistance (Ω)
0
0.0005
0.001
0.0015
Time (s)
60
61
62
63

FIG. 4

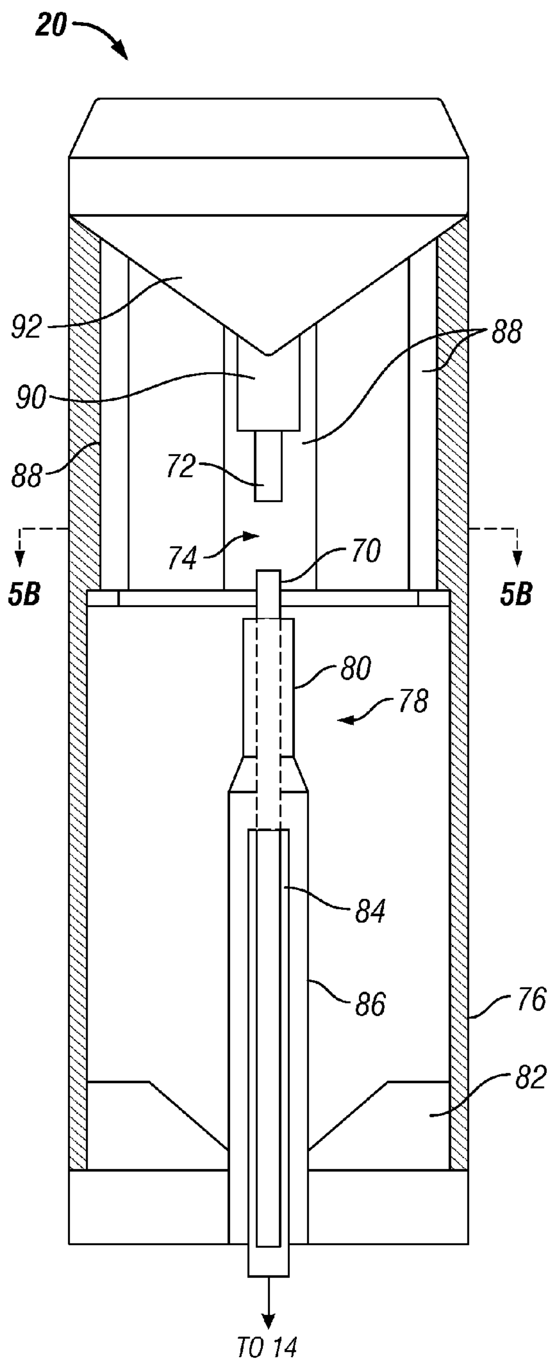

20
92
88
90
88
72
74
70
5B
5B
80
78
84
86
76
82
TO 14

FIG. 5A

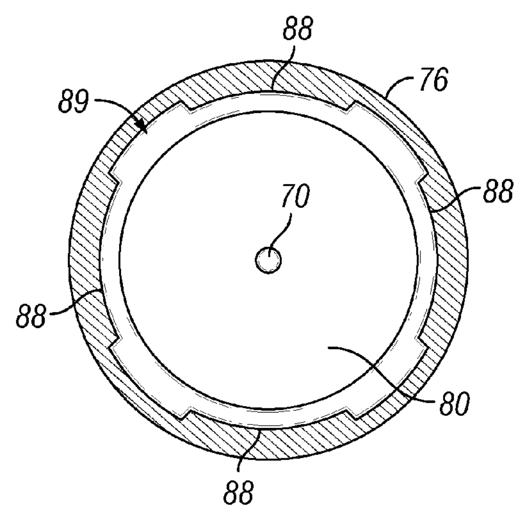

88
76
89
70
88
88
80
88

FIG. 5B

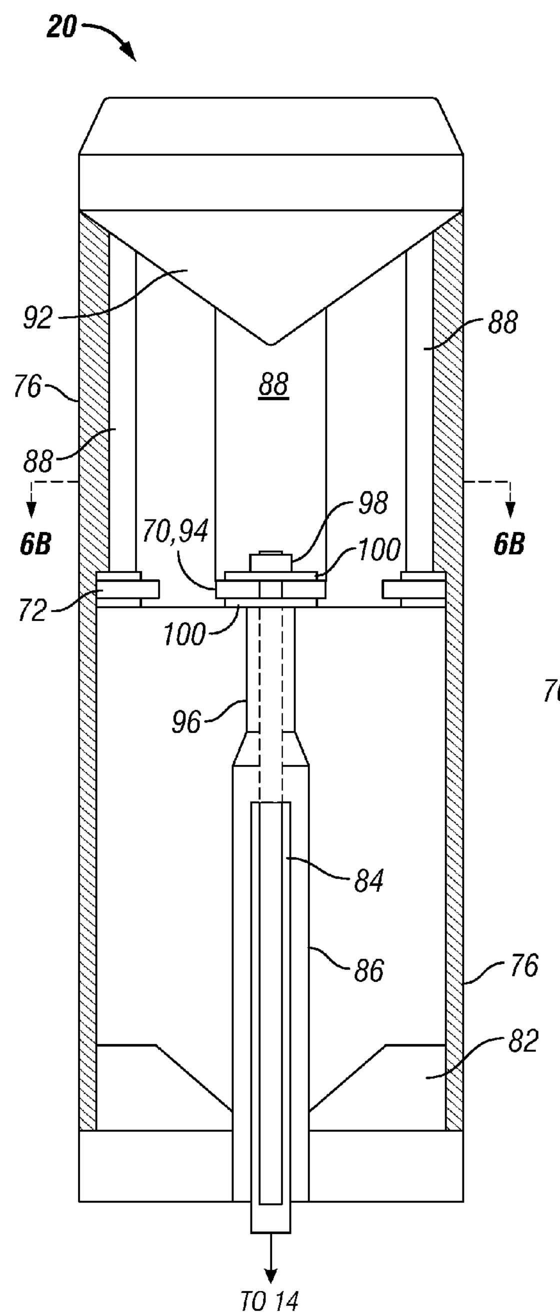

20
92
88
76
88
6B
98
70,94
100
6B
72
100
96
84
86
76
82
TO 14

FIG. 6A

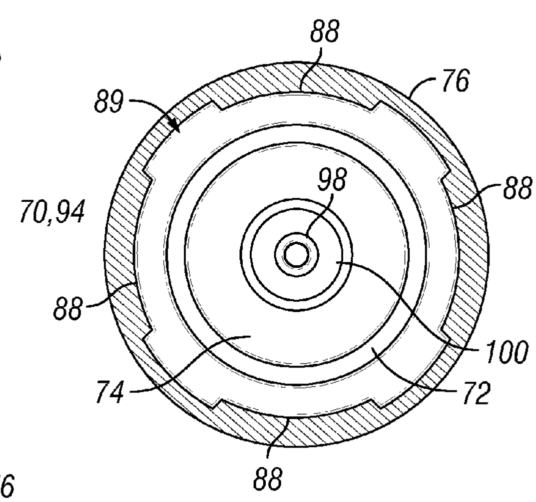

88
76
89
88
98
70,94
88
100
74
72
88

FIG. 6B

METHOD AND APPARATUS FOR GENERATING HIGH-PRESSURE PULSES IN A SUBTERRANEAN DIELECTRIC MEDIUM

PRIORITY CLAIMS

This application claims benefit under 35 USC 119 of U.S. Provisional Patent Application Nos. 61/801,304 with a filing date of Mar. 15, 2013 and 61/868,391 with a filing date of Aug. 21, 2013, the disclosures are incorporated herein by reference in their entirety.

FIELD

The present invention relates to a method and apparatus for using an electric pulse to generate a high-pressure pulse, typically of relatively long duration, in subterranean water or other dielectric media.

BACKGROUND

Fracturing of subterranean geological structures can be useful for assisting in the development of hydrocarbon resources from subterranean reservoirs. More particularly, in certain types of formations, fracturing of a region surrounding a well or borehole can allow for improved flow of oil and gas. A conventional method for causing such fracturing in the geologic structure involves generating hydraulic pressure, which may be a static or quasi-static pressure generated in a fluid in the borehole. Another conventional method includes generation of a shock in conjunction with a hydraulic wave by creating an electrical discharge across a spark gap. U.S. Pat. No. 8,220,537, titled "Pulse fracturing device and method," describes a fracture method that includes generating an acoustic wave in a fluid medium present in the borehole.

While conventional methods have been used successfully to form fractures, there is a continued need for an improved method and apparatus for generating high-pressure pulses in a subterranean medium and causing fracturing to occur.

BRIEF SUMMARY

The present invention provides an apparatus and method for generating high-pressure pulses in a subterranean dielectric medium, including electrical pulses of relatively long duration, e.g., greater than 100 μs and, in some cases, 4 ms or longer.

The method includes providing an electrode assembly in the medium. The electrode assembly has first and second electrodes that define a gap therebetween. A shaped electric current pulse having a duration greater than 100 μs is delivered to the electrode assembly so that an electric arc is formed between the first and second electrodes, and a pressure pulse is thereby produced in the medium. For example, a substantially constant current can be maintained during the duration of the current pulse duration and the duration of the electric current pulse can be between 200 μs and 4 ms. The electric current pulse can have a voltage between 10 kV and 30 kV and a current of at least 5 kA. Each electric current pulse can delivering at least 50 kJ of energy to the electrode assembly, and the pressure produced in the medium can be at least 1 kbar for a duration of at least 10 milliseconds. The delivery of the electrical current pulse can be repeated at a frequency of at least 1 Hz.

The dielectric medium can include fluids that are found in a wellbore used for recovery of hydrocarbons from a subterranean reservoir, such as one or more of water, saline water, oil, and drilling mud.

In some cases, the pressure of the medium is increased prior to delivery of the electric current pulse. For example, a fluid can be delivered to the medium to increase the pressure of the medium to at least 5 bars prior to the delivery of the electric current pulse. Also, the dielectric medium can be a fluid that is at least partially saturated with a gas, such as ammonia, sulfur dioxide, or carbon dioxide, so that the electric arc releases some of the gas from the dielectric medium during the production of the pressure pulse, thereby increasing the pressure and/or increasing the duration of the pressure pulse. The gas can occur naturally in the dielectric fluid or can be injected into the medium prior to the delivery of the electric pulse.

According to another embodiment, the disclosure provides an apparatus for generating high-pressure pulses in a subterranean dielectric medium. The apparatus includes an electrode assembly that is configured to be disposed in the medium. The electrode assembly has first and second electrodes that define a gap therebetween. A pulser is configured to deliver a shaped electric current pulse to the electrode assembly, wherein the electric current pulse has a duration greater than 100 μs, to form an electric arc between the first and second electrodes and thereby produce a pressure pulse in the medium. For example, the pulser can be configured to deliver the electric current pulse at a voltage between 10 kV and 30 kV and at a current of at least 5 kA. The pulser can be configured to maintain a substantially constant current during the duration of the current pulse duration, and the duration of the electric current pulse can be between 200 μs and 4 ms. The pulser can be configured to deliver at least 50 kJ of energy to the electrode assembly during the electric current pulse duration.

In some cases, the first and second electrodes of the electrode assembly are disposed in an axial configuration. Each electrode can have a diameter between 0.25 cm and 4 cm, and the electrodes can define an axial gap between 0.5 cm and 4 cm therebetween. In other cases, the electrode assembly the first and second electrodes are arranged in a radial configuration, with the first electrode disposed radially within a ring configuration defined by the second electrode. Each electrode can have a thickness between 0.2 cm and 2.5 cm, and the radial gap between the electrodes can be between 0.5 cm and 4 cm.

The pulser can include an inductive pulse-forming network and an opening switch configured to deliver the electrical current pulse to the electrode. The opening switch can be a solid-state electrical switch and/or a gas-based electrical switch. The pulser can be configured to deliver a plurality of electrical current pulse to the electrode assembly at a frequency of at least 1 Hz.

The apparatus can also include a pressure device configured to deliver a flow of fluid to the medium to increase the pressure of the medium to at least 5 bars.

In a typical operation, one or more electrical discharges or arcs are formed in the water or other dielectric media. Although the present invention is not limited to any particular theory of operation, it is believed that the arc vaporizes and ionizes the dielectric medium in the arc. It is also believed that the temperature of the medium's vapor increases, the size of the plasma channel increases, and a point is reached at which the impedance of the arc decreases rapidly with increasing current through the arc as the vapor ionizes. In some cases, the energy delivered to the dielectric medium may not be sufficiently increased by simply increasing the current because the electrical coupling efficiency (i.e., the ability to create a pressure pulse by the discharge of the electrical pulse in the medium) may decreases as the resistivity falls. However, it is believed that a good coupling efficiency can be maintained by limiting the peak value of the arc current and providing an initial, static pressure to the water so that the impedance of the water arc is maintained at an appropriate level. To deliver additional energy to the dielectric medium, the pulse duration of the arc can be increased while maintaining nearly constant current and, typically, generating a pressure in the medium that increases with time. Such arcs can be maintained stably for durations of at least several milliseconds. During this time, the impedance of the arc may either remain constant or slowly increase. By lengthening the duration of the pulse, it is believed that the total energy delivered to the medium can be increased, e.g., to achieve a desired degree of subterranean fracturing in a hydrocarbon production operation.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic view illustrating an apparatus for generating high-pressure pulses in a subterranean dielectric medium according to one embodiment of the present invention.

FIG. **2** is a schematic view illustrating the pulser of the apparatus of FIG. **1**.

FIG. **3** is a graphic illustration of the voltage and current applied by the pulser to the electrode assembly and flowing through an arc formed in water as a function of time during operation of an apparatus according to the present disclosure.

FIG. **4** is a graphic illustration of the impedance as a function of time of an electric arc formed in water during operation of an apparatus according to the present disclosure.

FIG. **5**A is a schematic view illustrating the electrode assembly of the apparatus of FIG. **1**.

FIG. **5**B is a sectional view of the electrode assembly of FIG. **5**A, as seen along line **5**B-**5**B.

FIG. **6**A is a schematic view illustrating an electrode assembly according to another embodiment of the present disclosure.

FIG. **6**B is a sectional view of the electrode assembly of FIG. **6**A, as seen along line **6**B-**6**B.

DETAILED DESCRIPTION

The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which some, but not all embodiments of the invention are shown. Indeed, this invention may be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

Referring to FIG. **1**, there is shown an apparatus **10** for generating high-pressure pulses in a subterranean dielectric medium according to one embodiment of the present disclosure. The apparatus **10** includes a pulser **12** that is configured to deliver a high voltage current through an electrical cable **14**, which can be disposed within a wellbore **16** that extends to a subterraneous hydrocarbon reservoir **18**. The cable **14** electrically connects the pulser **12** to an electrode assembly **20**, so that the pulser **12** can power the electrode assembly **20** and generate a pulse in the wellbore **16**.

The wellbore **16** can have portions that extend vertically, horizontally, and/or at various angles. Conventional well equipment **22** located at the top of the wellbore **16** can control the flow of fluids in and out of the wellbore **16** and can be configured to control the pressure within the wellbore **16**. The wellbore **16** can be at least partially filled with the medium, which is typically a fluid **24** such as water, and the equipment **22** can pressurize the fluid as appropriate.

The pulser **12** is connected to a power source **26**, e.g., a device configured to provide electrical power, typically DC. A controller **28** is also connected to the pulser **12** and configured to control the operation of the pulser **12**. The pulser **12** can include an electrical circuit that is configured to generate a shaped or tailored electric pulse, such as a pulse having a square (or nearly square) voltage profile, as shown in FIG. **3**. For example, as shown in FIG. **2**, the electrical circuit of the pulser **12** can include a plurality of capacitors **30***a*, **30***b*, **30***c*, **30***d* (collectively referred to by reference numeral **30**) and inductors **32***a*, **32***b*, **32***c*, **32***d* (collectively referred to by reference numeral **32**) that are arranged in parallel and series, respectively, to form a pulse-forming network ("PFN") **34**. The values of the capacitors **30** and inductors **32** can vary throughout the network **34** to achieve the desired pulse characteristics. For example, each of the capacitors **30***a* in a first group (or stage) of the capacitors can have a value C, such as 100 μF, and each of the inductors **32***a* in a first group (or stage) of the inductors can have a value L, such as 80 μH. Each of the capacitors **30***b* in a second group of the capacitors can have a lesser value, such as ½ C, and each of the inductors **32***b* in a second group of the inductors can have a lesser value, such as ½ L. Each of the capacitors **30***c* in a third group of the capacitors can have a still lesser value, such as ¼ C, and each of the inductors **32***c* in a third group of the inductors can have a still less value, such as ¼ L. Each of the capacitors **30***d* in a fourth group of the capacitors can have a still lesser value, such as ⅛ C, and each inductor **32***d* in a fourth group of the inductors can have a still less value, such as ⅛ L.

A ground of the PFN **34** is connected to the power source **26**, and the PFN **34** is configured to be energized by the power source **26**. An output **36** of the PFN **34** is connected to the cable **14** through a switch **38**, such as a solid-state IGBT switch or another thyristor, which is connected to the controller **28** and configured to be controlled by the controller **28**, so that the controller **28** can selectively operate the pulser **12** and connect the PFN **34** to the cable **14** to deliver a pulse to the electrode assembly **20**. For example, the switch **38** can be a device that is capable of handling a peak voltage of at least 20 kV, a maximum current of at least 20 kA, and a maximum charge of at least 100 C. Such IGBT switches can be assembled by placing commercially available IGBTs in series and parallel in order to obtain the necessary voltage and current handling capabilities. In some cases, other types of switches may be usable, such as gas switches of a sliding spark design.

It is also appreciated that the pulser **12** can use other energy storage devices, other than the illustrated PFN **34**. For example, while the illustrated embodiment uses capacitive energy storage based on a Type B PFN configuration, it is also possible to use a PFN based on inductive energy storage and a solid-state opening switch. An inductive PFN could allow a smaller design and could also allow a lower voltage during the charging phase (e.g., a typical charging voltage of about 1 kV in the inductive PFN instead of a typical charging voltage of about 20 kV in a capacitive PFN) and only operate at high voltage for a short period (such as a few microseconds) during the opening of the switch **38**.

The controller **28** can repeatedly operate the pulser **12** to deliver a series of discrete pulses. One typical repetition rate is about one pulse per second, or 1 Hz. In other cases, the pulser **12** can be operated more quickly, e.g., with a repetition rate as fast as 5 Hz or even faster, depending on the need of the particular application. If a much lower repetition rate is acceptable (such as less than 0.1 Hz), then other electrical gas switches that are unable to provide fast repetition may be usable.

The pulser **12** can be actively or passively cooled. For example, as shown in FIG. **2**, the pulser **12** can be disposed in an enclosure **40** that is filled with a thermally conductive fluid **42** such as oil that cools the pulser **12**. Additional equipment, such as a radiator and/or fans, can be provided for actively cooling the oil **42**. In other cases, the pulser **12** can be air-cooled.

In one embodiment, the pulser **12** is configured to operate with an output voltage of between 10 kV and 30 kV, such as about 20 kV. The pulser **12** can generate a peak current between 10 kA and 20 kA, such as between 12 kA and 15 kA, depending on the impedance of the impedance of the cable **14** and the impedance of the arc generated in the dielectric fluid. The impedance of the PFN **34** can be matched to the expected impedance load at the electrode assembly **20**, e.g., between 0Ω and 1Ω, such as between 0.5Ω and 0.9Ω. In another case, the peak current was kept below about 20 kA and the medium was pressurized, resulting in an impedance between 0.1Ω and 0.4Ω.

FIG. **3** shows the electrical waveform of a typical voltage pulse **50** and a typical current pulse **51** during operation of the apparatus **10**. The current pulse **51** has a pulse width **52** that is determined, at least partially, by the number of elements in the PFN **34** shown in FIG. **2**. The magnitude of the current **53** is determined, at least partially, by the values of the capacitors **30** and inductors **32** of the PFN **34**. The rise time **54** of the current waveform **51** is determined, at least partially, by the first-group elements **30***a*, **32***a* of the PFN **34**.

FIG. **4** shows the impedance **60** of one typical water arc as a function of time during operation of the apparatus **10**. The rapid fall time of the impedance **62** is driven by the rapid rise of the current **54**. The pulse width of the current **52** is reflected in the impedance as the pulse width of the impedance **62**. The average magnitude of the impedance **63** is determined, at least partially, by the electrode geometry, the peak current **53**, and the static pressure applied to the load. The average impedance **63** is nearly constant (even slightly increasing) with time.

The current can be maintained at a substantially constant level for the duration of the pulse. The pulse can be maintained to achieve a pulse length, or duration, of greater than 100 μs. For example, the embodiment between 200 μs and 4 ms. Further, in other embodiments, the pulser **12** can provide a pulse duration of more than 4 ms, e.g., by adding additional capacitors **30***a* in the first group of capacitors.

Although other configurations of the PFN **34** are possible, the illustrated configuration is known as a pulsed current generator in a Type B PFN configuration, which can provide a substantially constant current pulse to electrode assembly **20** and the art formed therein through the dielectric medium. The PFN-based pulser **12** allows control of the current that drives the discharge.

Although the present invention is not limited to any particular theory of operation, it is believed that the highest value capacitors **30***a* and inductors **32***a* can provide or define the basic pulse shape and the pulse duration, and the other capacitors **30***b*, **30***c*, **30***d* (and, optionally, additional capacitors) and inductors **32***b*, **32***c*, **32***d* (and, optionally, additional inductors) reduce the rise time of each pulse provided by the PFN **34**. More particularly, the rise time can be determined by the rise time of the first group of capacitors **30***a* and inductors **32***a*. The PFN **34** can be designed to have a rise time of less than 100 μs, such as between 20 μs and 75 μs, typically between 25 μs and 50 μs, depending on the inductance of the cable **14**, the smallest capacitance in the PFN **34**, and the load at the electrode assembly **20**. In general, shorter rise times can be effective, while longer times tend to have higher levels of break down jitter and longer delays between the application of voltage to the electrodes and the development of an arc.

An appropriate selection of the values of the capacitors **30** and inductors **32** in the PFN **34** can limit the peak current that the PFN **34** delivers. This is the effect of the impedance of the PFN **34**, where the PFN **34** impedance (Z_{PFN}) is given as follows:

$$Z_{PFN} = \sqrt{\frac{L}{C}},$$

where L can C are the inductance and capacitance of the PFN **34**.

In a typical case, values of Z_{PFN} are roughly in the range of 0.5Ω to 1Ω. Typically, the rise time of the current pulse from the PFN **34** is proportional to the square root of the LC of the individual elements of the PFN **34**. For a load impedance greater than the impedance of the PFN **34**, the rise time (t_{rise}) can be about ¼ the LC period, given as follows:

$$t_{rise} \cong \frac{\pi}{2}\sqrt{LC}$$

The peak current (I_{peak}) of an element of the PFN **34** can be proportional to the voltage on the capacitor (V_0), the square root of the capacitance in inversely proportional to the square root of the inductance of the element of the PFN **34** (if the impedance of the PFN **34** is larger than the load impedance), as follows:

$$I_{peak} = \frac{V_0}{Z_{PFN}} = V_0\sqrt{\frac{C}{L}}.$$

In the illustrated embodiment, the PFN **34** is modified to have smaller capacitors **30***b*, **30***c*, **30***d* and inductors **32***b*, **32***c*, **32***d* precede the main set of capacitors **30***a* and inductors **32***a* to provide improved current rise time. Thus, the smaller-value capacitors **30***b*, **30***c*, **30***d* and smaller-value inductors **32***b*, **32***c*, **32***d* can be selected with values that are sized to maintain the same value of current but will provide a smaller time to peak current as the first few elements in the PFN **34**. By using this approach, the modified PFN can be made to have a rise time less than 50 μs and yet having a total duration ranging from about 200 μs to several ms. The total energy (E) stored in the PFN **34** can be the sum of the energies stored in all of the capacitors of the PFN **34** and is expressed as follows:

$$E = 0.5\ V^2 \sum_{i=1}^{n} C_i.$$

The energy coupled to the dielectric medium discharge can reach or even exceed 500 kJ for reasonable PFN **34** parameters and charge voltages. The number of capacitors **30** inductors **32** in the PFN **34** can determine the pulse length of the current pulse delivered to the arc. The pulse width of the PFN **34** can be determined by the sum of the capacitances and inductances of the entire PFN **34**. For example, in the illustrated embodiment, the duration of each pulse, or pulse width (t_{pw}), of the PFN **34** is given as follows:

$$t_{pw} = 2\left(\sum_{i=1}^{n} L_i \sum_{i=1}^{n} C_i\right)^{0.5}.$$

In one example, the pulse width is between about 1 ms and 4 ms, the total capacitance of the PFN **34** is between about 1 mF and 4 mF, the peak current is about 15-18 kA, and the total inductance of the PFN **34** is between about 0.4 mH and 1.6 mH. In other cases, where less energy is required and a shorter pulse is desirable, the number of stages of first-group capacitors **30***a* and first-group inductors **32***a* can be reduced to decrease the pulse length and stored energy. One such embodiment would use only 5 capacitors **30***a* and 5 inductors **32***a* in the first group, together with the faster stages (**30***b*, **30***c*, **30***d* and **32***b*, **32***c*, **32***d*) to generate a 1-ms pulse.

The total energy of the pulse can also be varied according to the fracturing needs of a particular reservoir. In some cases, the total energy of each pulse can be between 50 kJ and 500 kJ, e.g., 450 kJ. The total energy per pulse can be reduced, if needed, by reducing the number of the capacitors **30***a* in the first group of the PFN **34**, or the energy per pulse can be increased by adding to the number of the capacitors **30***a* in the first group of the PFN **34**.

It is appreciated that the pulser **12** can be optimized to provide a pulse length (by adjusting the number of groups of capacitors **30** and inductors **32** in the PFN **34**), rise time (by adjusting the size of the smaller-value capacitors **30***b*, **30***c*, **30***d* and inductors **32***b*, **32***c*, **32***d* in the PFN **34**), maximum voltage, and repetition rate depending on the specific application and manner of use. Generally, it is believed that a current greater than about 20 kA for pulses in water may result in arc impedances that are too low for efficient energy coupling. On the other hand, arc currents that are too low may be subject to uncontrolled arc quenching for longer pulses. The electrode assembly **20** is connected to the cable **14** and configured to create one or more electric arcs when the electric pulse is delivered via the cable **14**. For example, FIGS. **5**A and **5**B show an electrode assembly **20** configured to form an electric arc between a first (or high voltage) electrode **70** and a second (or ground) electrode **72** that are positioned with an axial gap **74** therebetween. The electrodes **70**, **72** are disposed in assembly housing **76** so that the electric arc can be formed across the gap **74** therebetween in the axial direction of the electrode assembly **20**. The first electrode **70** is mounted in a conducting electrode holder **78**, e.g., by a press fit. The first electrode **70** and the holder **78** are disposed in an insulator **80**, such as high-density polyethylene (HDPE), which is retained in the assembly housing **76** with a compression ring **82**. The cable **14** is connected to the first electrode **70** via the electrode holder **78** with an electrical connector **84**. The electrical connector **84** is surrounded by an insulative material **86**, such as a highly compressed, oil-saturated foam **29**. The assembly housing **76** has a plurality of circumferentially spaced vanes **88** that electrically and mechanically connect the lower portion of the assembly housing **76** to the second electrode **72** by way of a conductive electrode mounting **90** and a conductive shock reflecting base **92**. As shown in FIG. **5**B, the vanes **88** define gaps **89** therebetween so that the pressure pulse can be transmitted outside the housing **76** to the dielectric medium **24** in the wellbore **16**. In other embodiments, the vanes **88** can be smaller or larger than as shown in FIG. **5**B.

FIGS. **6**A and **6**B illustrate another embodiment of the electrode assembly **20** in which the electrodes **70**, **72** are configured in a radial arrangement so that the arc is formed radially. In this case, the first electrode **70** includes a cylindrical element **94** mounted on a conducting base **96** via a bolt **98**, with retaining members **100** disposed axially opposite the cylindrical element **94**. The second electrode **72** extends circumferentially on the inner surface of the housing **76**, with the gap **74** defined radially between the first and second electrodes **70**, **72** so that the arc can be formed in the radial direction.

The dimensions of the insulator **80** can be designed according to the structural and electrical requirements of the electrode assembly **20**. In the illustrated embodiment, the diameter of the insulator **80** is about 10 cm, and the length of the insulator **80** is typically equal to or greater than its diameter. A variety of insulative materials can be used for the insulator **80**, such as Polytetrafluoroethylene (PTFE), available under the trade name, Teflon®, which is a mark of E. I. du Pont de Nemours and Company, high-density polyethylene (HDPE), ultra-high-molecular-weight polyethylene (UHMW PE), and nylon.

The overall dimensions and specifications of the electrode assembly **20** can be designed according to its intended use and the parameters of its individual components. In some cases, the first electrode **70** can have a diameter of between 0.5 cm and 5 cm, such as about 1 cm. The first electrode **70** typically has a relatively small portion of exposed surface area exposed to the dielectric fluid to minimize current leakage between the time when a voltage is applied to the electrode assembly **20** during the electric pulse until the electric discharge in the dielectric fluid begins.

In the illustrated embodiment, the positive voltage is applied to the first electrode **70** and the second electrode **72** is grounded, as it is believed that the negative electrode may tend to erode more quickly than the positive electrode. The second (ground) electrode **72** typically has a diameter that can be the same or larger than the first electrode **70**. The second electrode **72** can include additional mass to help extend the useful lifetime of the electrode **72** and the electrode assembly **20**.

The electrodes **70**, **72** can be configured to define with a gap **74** therebetween within the range of 0 to 5 cm, typically between 1 cm and 3 cm, such as about 2 cm. During use of the electrode assembly **20**, the electrodes **70**, **72** can erode, and the gap **74** can increase. As the gap **74** increases, the impedance of the dielectric fluid between the electrodes **70**, **72** will also increase. Upon a certain amount of erosion from the electrodes **70**, **72**, e.g., when the gap **74** becomes 2.5 cm or more, the electrode assembly **20** can be refurbished or replaced.

The electrodes **70**, **72** are typically formed of a material that is sufficiently mechanically robust to withstand multiple pulses from the pulser **12**. Such materials include steels (e.g., stainless steel or hard carbon steels), refractory metals (such as tungsten, tantalum, or tungsten alloys), nickel alloys (such as an alloy available under the tradename Hastelloy®, a trademark of Haynes International, Inc.) and carbon (such as graphite or carbon-carbon composites). Refractory alloys of tungsten have been observed to erode at a relatively low rate. In particular, the electrodes **70**, **72** can be made of a material formed of a mixture of tungsten and up to 10% copper. For example, one such alloy is commercially available under the trade name Elkonite® 50WC, a trademark of CMW International Inc. The electrode assembly **20** is also typically designed to be capable of withstanding static pressure up to 100 bars and a peak dynamic pressure of at least 1 kbar.

As shown in FIG. **1**, the pulser **12** is connected to the electrode assembly **20** via the cable **14**. The cable **14** is typically a low-impedance electrical conductor, which includes one or more electrical conductors in an insulative sheath. The impedance of the electrical connections and conductors can be less than the impedance of the electrode assembly **20** (including the impedance across the gap **74** between the electrodes **70**, **72**) and the effective combined impedance of the capacitors **30** and inductors **32** so that the stored electrical energy is effectively coupled to the arc formed across the gap **74**.

In use, the pulser **12** can deliver an electric current pulse to the electrode assembly **20** so that an electric arc is formed across the gap **74** between the electrodes **70**, **72** and the electrode assembly **20** thereby produces a pressure pulse in the fluid **22**. Electrical pulses of long duration and high energy can be used to produce pressure pulses that are also long in duration and of high pressure.

The apparatus **10** can be used to generate such pulses in various types of dielectric media, such as media that include water; saline water; oil; freon and silicon oils; mixtures of oil and water; mixtures of oil, water, & drilling mud; liquid or solid plastics; and mixtures of any of the foregoing, with or without dissolved gases. For example, in the case of a wellbore **16** used for producing hydrocarbons from a subterranean reservoir, the wellbore **16** can be filled with a naturally occurring mixture that is predominantly water, or fluids can be injected into the wellbore **16** to increase the effectiveness of the pulsing operation.

Dissolved gas in the medium can result in increased pressure generation. It is believed that some of the dissolved gas can be released from a liquid medium when the liquid medium is shocked to either higher or lower pressures. Dissolved gas may be naturally occurring in the medium and/or injected into the medium for that purpose. For example, dissolved ammonia, sulfur dioxide, or carbon dioxide can be injected in the medium at any amounts, potentially up to the saturation limit of the medium. In water, a 10% molar fraction of dissolved gas can be achieved readily at pressures above 1 bar at room temperature. The application of 100's of kJ of energy to the water together with a shock wave that generates strong cavitation can release much of the dissolved gas(es) in the dielectric medium within a period of 100 μs-500 μs. This can provide a relatively continuous increase in pressure in the time following the shock that can result in a pressure pulse that lasts more than 10 ms. Some solid hydrates exhibit a similar behavior and can be used in a similar fashion.

In one embodiment, where the wellbore **16** contains a dielectric medium that is mostly water, a gas is provided in the medium in a concentration of greater than 1% molar fraction of ammonia, sulfur dioxide, or carbon dioxide. The heating of the medium by the electrical discharge can release several moles of gas from the volume of the electrode assembly **20**, e.g., more than 44 liters of gas at standard temperature and pressure. In the same dielectric medium, when pressurized to 100 bars and a temperature of 100 C, a gas volume of about 1 liter can be released, such volume being comparable to the volume of the chamber defined within the electrode assembly **20**. The generation of one or more liters of gas can create a long duration pressure pulse, e.g., extending for 10 ms or longer and far beyond the duration of the electric pulse.

A pressure device **110** can be connected to the well equipment **22** and configured to pressurize the dielectric medium to an increased pressure before the pulsing operation. For example, the pressure device **110** can be a fluid delivery device that is configured to inject a hydraulic, pneumatic, or other fluid to vary the pressure in the wellbore **16** and thereby optimize the coupling of the electrical energy to the arc and, hence, the magnitude and/or duration of the electro-hydraulic dynamic pressure that is generated by the electrical discharge. For example, prior to and during the electrical discharge by the apparatus **10**, a static pressure can be applied to the dielectric medium, or a slow-pulse quasi-static pressure can be applied to the dielectric medium. In some cases, the pressure device **110** can increase the pressure of the dielectric medium in the wellbore **16** to an absolute pressure of between 5 and 100 bars during the pulsing operation. In other cases, the pressure device **110** can be configured to provide even higher pressures, such as to 200 bars, e.g., in deeper reservoirs where the naturally occurring pressure is high. It is believed that, the apparatus **10** can develop arcs in pressurized water that have a higher impedance than typical arcs in water at lower pressures. It is also believed that the initial pressure in the medium can retard the early-time expansion of the arc plasma. Later, the increase in dynamic pressure generated by the arc itself can feed back on the arc dynamics and continue to confine the now-hotter arc channel.

Although the present invention is not limited to any particular theory of operation, it is believed that short-pulse electrical discharges are limited in the amount of electrical power that can be efficiently coupled to a resistive water arc. As the arc current is raised to increase electrical power (and the energy delivery per pulse), the resulting electrical heating of the water arc plasma decreases the impedance of the arc both through the Spitzer resistivity (ρS) which scales inversely with plasma temperature (T) to the 3/2 power, and also by increasing the diameter of the discharge driven by pressure balance. The Spitzer resistivity is defined as follows:

$$\rho_S = \frac{\bar{Z}\ln\Lambda}{T^{3/2}}.$$

The Spitzer resistivity effectively becomes proportional to T3/2 because the plasma parameter, ln Λ, is a very weakly varying function of density and temperature and in this case ranges from 1 to 4, and Z is the average ionization level of the plasma and is typically about 1 for water arcs. The total impedance of the arc channel is inversely proportional to the mean cross-sectional area of the arc and proportional to the length of the arc. Heating the water-arc plasma increases the plasma pressure and expands the arc against the water and decreases the overall arc impedance. Dynamic pressure balance sets the time-dependence of the arc diameter and, hence, the arc area.

In operation, it is believed that a short time delay can occur after a voltage pulse is applied to the conducting electrodes **70**, **72** and before the arc forms in the dielectric medium across the gap **74** between the electrodes **70**, **72**. This delay can be in the range of 50 μs to several hundred microseconds. Once a breakdown occurs, the voltage across the electrode gap **74** (i.e., the arc) drops and the current rapidly increases to a maximum voltage, as determined by the PFN **34** and the impedance of the arc. This is due to the rapid change in the impedance of the arc in time. The impedance can fall to a nearly steady-state value that is determined by the length of the discharge, the peak current of the discharge, the electrode geometry (field enhancement), the initial static pressure, and the final dynamic pressure on the arc. Because the duration of the current pulse is much longer than the acoustic time of the system, the arc can see an increase in the dynamic pressure during the pulse. Thus, later in time, the pressure in the system is higher and the arc impedance is able to remain substantially constant over a long period of time.

In some cases, an active trigger system may be desirable. For example, a liquid with a high conductivity may cause significant energy loss from the PFN **34** before the arc initiates. In that case, the apparatus **10** can include an active trigger feature, which involves the application of voltages of order 50 kV or greater to the electrodes **70**, **72**, to reduce the resistive losses in the conducting dielectric medium.

The initial formation and heating of the arc can generate a high-pressure shock, and the pressure shock can be characterized by a relatively short rise time, such as a rise time of less than 50 μs. The duration of the electrical drive pulse is typically longer than the acoustic transit time of the system. The multiple shocks that are generated in the arc can equilibrate and create a long-duration, dynamic pressure pulse on the system. The dynamic pressure in the system can tend to increase as long as electrical energy is delivered to the load. When the input electrical energy from the pulser **12** ceases, the pressure begins a relatively slow decay, with the decay time typically depending on the specific mechanical details of the system. In testing, energies above 100 kJ delivered to a load region resulted in generation of pressures greater than 1 kbar (15 kpsi) in an enclosed or substantially enclosed chamber with a volume of about 1 liter. It is believed that lower peak pressures and shorter pressure durations would be generated in a larger-volume configuration, such as would typically be present in the wellbore **16**. Higher peak pressures are possible if the total volume is smaller and/or if more energy is delivered to the load.

It is also believed that the electrode dimensions (length and diameter for axial electrodes **70**, **72** as shown in FIG. **5**, and axial height and radial length for radial electrodes **70**, **72**, as shown in FIG. **6**) can have several significant effects on the performance of the apparatus **10**. First, the diameter of axial electrodes **70**, **72** and the electrode spacing can determine, at least partially, the average electric field strength seen at the surface of the electrodes **70**, **72**. It is believed that a higher electric field at the surface of the electrode **70** typically correlates with a more rapid formation of the electrical arc. Thus, if it is desirable to have a large geometrical field enhancement for a particular application, smaller diameter electrodes **70**, **72** may be preferred. Second, larger electrode diameter for an axial electrode **70**, **72** typically correlates with more electrode mass being available to erode during many discharges (e.g., hundreds of discharges during hundreds of operations of the electrode assembly **20**). To reduce erosion, it may be desirable to have the largest-diameter, most massive electrode **70**, **72** reasonably possible while staying within other design constraints. Third, leakage current in conductive water (e.g., salinity greater than 1000-ppm total dissolved solids) can be reduced if the total area of the high-voltage electrode **70** is reduced. Thus, in some cases, it may be desirable to minimize the surface area of the high-voltage electrode **70** to reduce leakage current. It is appreciated that the three above-noted drivers for the design of the electrode dimensions are partly conflicting. For example, if a small electrode diameter is chosen to reduce leakage prior to arcing, the electric field enhancement may be too low, there may be a very slow development of the precursor streamers that eventually form arcs, and the arcs that do form may have very little preferential direction. In extreme cases, arcs may propagate from the high-voltage electrode **70** to any adjacent ground location. Also, if the diameter of the electrode **70** is too small, then the useful lifetime of the electrode **70** may be short due to excessive erosion. On the other hand, if the diameter and length of the first electrode **70** are too large, then the leakage current may be very large, and too much energy may be lost before the arc forms.

A rapid current rise time can help minimize the unwanted parasitic arcs and reduce the delay between the application of the voltage to the electrodes **70**, **72** and the formation of an arc for larger diameter electrodes **70**, **72**. One way to minimize the leakage current from the first electrode **70** is to coat the electrode **70** with an appropriate insulating material, such as epoxy, e.g., thermosetting resin available under the trade name of Scotchcast®, a trademark 3M Company. That is, the curved, radially outward surface of the electrode **70** can be coated, and the coating can erode away as the electrode **70** erodes. In tests, a coated electrode **70** having a diameter of about 2.5 cm was demonstrated to work well when pulsed with an electric pulse having a rise time of about 50 μs or less.

Many modifications and other embodiments of the invention set forth herein will come to mind to one skilled in the art to which this invention pertains having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the invention is not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.

What is claimed:

1. A method for generating high-pressure pulses in a subterranean dielectric medium, the method comprising:

providing an electrode assembly in the dielectric medium, the electrode assembly having an assembly housing, the electrode assembly further having a first electrode positioned within and supported by the assembly housing and having a second electrode positioned within the assembly housing, wherein the first and second electrodes of the electrode assembly are arranged in a radial configuration, with the first electrode disposed radially within a ring defined by the second electrode, and a radial gap between the first and second electrodes, wherein the first electrode and the second electrode have a cylindrical shape, and wherein at least one of the first electrode and the second electrode have an axial length of at least 10 millimeters; and

delivering a shaped electric current pulse from a pulser to the electrode assembly, the electric current pulse having a duration greater than 100 μs and maintaining a substantially constant current during the duration of the electric current pulse, such that an electric arc is formed between the first and second electrodes, and thereby producing a pressure pulse in the dielectric medium, wherein the pulser further comprises a pulse-forming network including a plurality of capacitors arranged in parallel and a plurality of inductors arranged in series.

2. The method of claim **1** further comprising, prior to the step of delivering the electric current pulse, delivering a fluid to the dielectric medium to increase the pressure of the medium to at least 5 bars.

3. The method of claim **1** wherein the step of delivering the electric current pulse comprises forming the electric arc through the dielectric medium comprising a fluid that is at least partially saturated with a gas comprised of at least one of the group consisting of ammonia, sulfur dioxide, and carbon dioxide, such that at least some of the gas in the fluid of the dielectric medium is released during the production of the pressure pulse.

4. The method of claim **1** wherein the step of delivering the electric current pulse comprises delivering a voltage between 10 kV and 30 kV to the electrode assembly.

5. The method of claim **1** wherein the step of delivering the electric current pulse comprises delivering a current of at least 5 kA for the electric current pulse duration.

6. The method of claim **1** wherein the duration of the electric current pulse is between 200 μs and 4 ms.

7. The method of claim **1** wherein the dielectric medium comprises at least one of the group consisting of water, saline water, oil, or drilling mud.

8. The method of claim **1** wherein the step of delivering the electric current pulse comprises delivering at least 50 kJ of energy to the electrode assembly during the electric current pulse duration.

9. The method of claim **1** wherein the step of delivering the electric current pulse and producing the pressure pulse in the medium comprises producing a pressure of at least 1 kbar for a duration of at least 10 milliseconds in the medium.

10. The method of claim **1** further comprising repeating the step of delivering the electric current pulse to the electrode assembly at a frequency of at least 1 Hz.

11. The method of claim **1** wherein each electrode having a thickness between 0.2 cm and 2.5 cm and the radial gap between the first and second electrodes being between 0.5 cm and 4 cm.

12. An apparatus for generating high-pressure pulses in a subterranean dielectric medium, the apparatus comprising:

an electrode assembly configured to be disposed in the dielectric medium, the electrode assembly having an assembly housing, the electrode assembly further having a first electrode positioned within and supported by the assembly housing and having a second electrode positioned within the assembly housing, wherein the first and second electrodes of the electrode assembly are arranged in a radial configuration, with the first electrode disposed radially within a ring defined by the second electrode, and a radial gap between the first and second electrodes, wherein the first electrode and the second electrode have a cylindrical shape, and wherein at least one of the first electrode and the second electrode have an axial length of at least 10 millimeters; and

a pulser configured to deliver a shaped electric current pulse to the electrode assembly, the electric current pulse having a duration greater than 100 μs and maintaining a substantially constant current during the duration of the electric current pulse, to form an electric arc between the first and second electrodes and thereby produce a pressure pulse in the dielectric medium, wherein the pulser further comprises a pulse-forming network including a plurality of capacitors arranged in parallel and a plurality of inductors arranged in series.

13. The apparatus of claim **12** further comprising a pressure device configured to deliver a flow of fluid to the medium to increase the pressure of the dielectric medium to at least 5 bars.

14. The apparatus of claim **12** wherein the pulser is configured to deliver the electric current pulse at a voltage between 10 kV and 30 kV.

15. The apparatus of claim **12** wherein the pulser is configured to deliver the electric current pulse at a current of at least 5 kA.

16. The apparatus of claim **12** wherein the duration of the electric current pulse is between 200 μs and 4 ms.

17. The apparatus of claim **12** wherein the pulser is configured to deliver at least 50 kJ of energy to the electrode assembly during the electric current pulse duration.

18. The apparatus of claim **12** wherein each electrode having a thickness between 0.2 cm and 2.5 cm and the radial gap between the first and second electrodes being between 0.5 cm and 4 cm.

19. The apparatus of claim **12** wherein the pulser is configured to deliver a plurality of electric current pulses to the electrode assembly at a frequency of at least 1 Hz.

20. The apparatus of claim **12** wherein the pulser comprises a solid-state electrical switch configured to deliver the electric current pulse to the electrode assembly.

21. The apparatus of claim **12** wherein the pulser comprises a gas-based electrical switch to deliver the electric current pulse to the electrode assembly.

22. The apparatus of claim **12** in which the pulser comprises an inductive pulse-forming network and an opening switch configured to deliver the electric current pulse to the electrode assembly.

* * * * *